BIOENERGY FOR ELECTRICITY GENERATION

Presented by Jennifer Den

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Abstract

Energy from biological materials addresses a number of key energy and environmental issues, including climate change, energy security, and replacement of carbon-intensive energy sources. This thesis assesses the feasibility of using three types of biological material for U.S. electricity generation: wood chips, biofuels, and organic waste. To evaluate economic feasibility, this paper examines system design, feedstock availability, and other advantages and disadvantages of alternative biological feedstocks. It also discusses three cost-benefit studies evaluating wood chips, biofuels, and waste-to-energy. This thesis recommends that the U.S. electricity sector consider investing in additional use of wood chips and organic waste and continue developing research for next-generation biofuel. Wood chips can cost less than heating oil. Municipal solid waste as a fuel could manage and reduce carbon. Although next-generation biofuels are more expensive in terms of capital and operating costs than conventional biofuel and fossil fuels, their use could mitigate food security and environmental concerns. All three technologies are used globally, proving technical feasibility. The availability of wood and waste in the U.S. offers another incentive for feedstock. Additional funding and research remain challenges for next-generation biofuel. Future research in bioenergy could include cost-benefit and carbon emission analyses that incorporate additional production pathways, comparisons to current renewable feedstocks, and recommended sites for the three technologies this paper addresses.

RENEWABLE ENERGY FOR ELECTRICITY GENERATION

Renewable energy is defined as energy collected from sources that can be replenished continually or annually (International Energy Agency, 2016). It can be used to generate electricity, heat or cool air or water, transport people or materials, or provide off-grid (rural) services (Renewable Energy Policy Network for the 21st Century, 2010). This discusses electricity generation from renewable energy fuels.

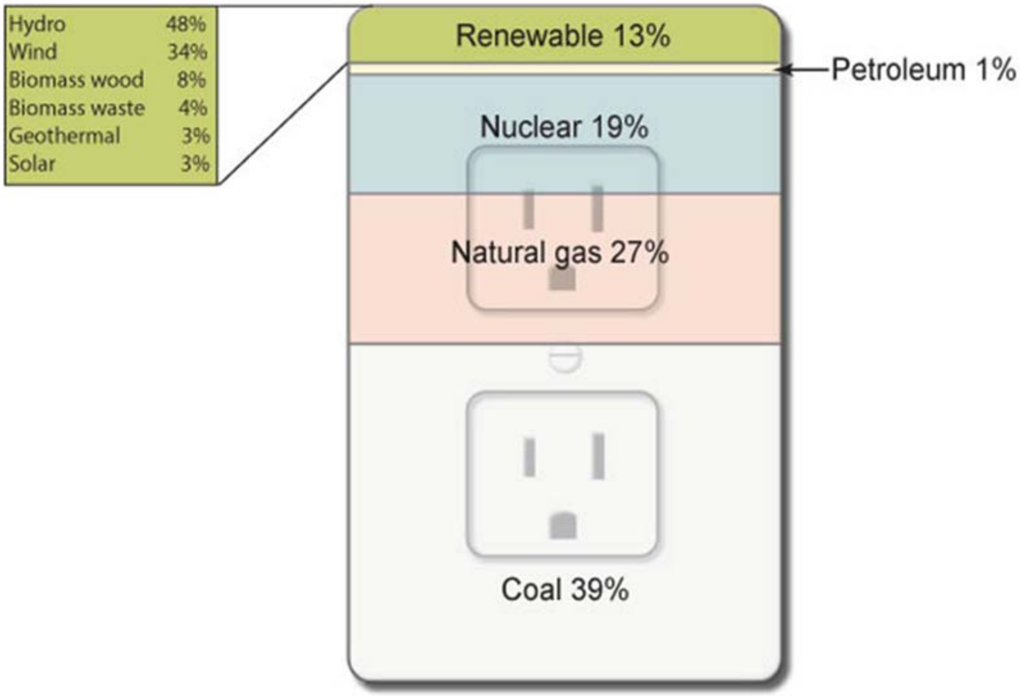
Although fossil fuels remain the primary fuel source to produce electrical power within the U.S. and worldwide, clean and renewable sources, such as hydroelectric, wind, solar, geothermal, and bioenergy, have become more widespread. Some notable U.S. government policies that support this process include the Energy Independence and Security Act (EISA) of 2007, America's Clean Energy and Security Act (ACES) of 2009, and the Recovery and Reinvestment Act (2009). These policies were passed to create clean energy jobs, enable energy independence, promote research, increase energy efficiency and performance, reduce greenhouse gas (GHG) emissions, and transition to a clean energy economy.

Current sources of U.S. electricity generation include coal (39 percent), natural gas (27 percent), nuclear (19 percent), renewables (13 percent), and petroleum (1 percent). Renewables are composed of 48 percent hydro, 34 percent wind, 8 percent wood, 4 percent waste, 3 percent geothermal, and 3 percent solar (see Figure 1) (U.S. Department of Energy, Energy Information Administration, 2015b). This paper will focus on bioenergy, which includes wood, waste, and biofuel.

According to the International Energy Agency (IEA), bioenergy, renewable energy produced by organic matter, provides 10 percent of the world's primary energy supply, making it the largest renewable energy source. In some poor developing countries, biological material remains a common fuel source for heat and space heating (IEA, 2006). However, bioenergy has become a viable and close to carbon neural option for electricity generation in developed countries like the United States. Bioenergy can be converted into different forms (solid, liquid, and gas) from local and often abundant resources. Harvesting and using the many different types of biological material have benefits that range from stabilizing soil fertility to managing waste disposal. Because of these reasons as well as growing interest in this area of research, the utilities sector should consider including more bioenergy into the electrical fuel mix.

Different sources of bioenergy (i.e. wood chips, biofuels, etc.) require distinct technical methods to convert the raw material to electricity. These processes will be discussed for each source. Studies that conduct a cost-benefit analysis will be used to examine economic parameters (cost, resource availability, etc.), technical feasibility (design, potential production scale), and environmental impacts. If the net economic benefits of using one or more of these processes are favorable compared to fossil fuels, bioenergy for electricity generation should be a feasible option.

Figure 1. U.S. Electricity Generation Mix, 2014



Source: Reprinted from "Electric Power Monthly" by the U.S. Department of Energy, Energy Information Administration, 2015, Retrieved from https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_1

BIOLOGICAL MATERIAL AND BIOENERGY

Biological materials refer to substances derived from living organisms that can be harnessed to produce bioenergy. Bioenergy can be generated through biomass (solid), biogas (gas), or biofuel (liquid). To generate energy, all three undergo thermochemical processes and follow a similar chemical equation (Carnegie Mellon University, 2003):

Biomaterial + Oxygen $\rightarrow$ Carbon Dioxide + Water + Heat Equation 1

Biomass originates from organic material, which may include wood, manure, crops, garden waste, or other agricultural byproducts (Guo, 2014). The energy in organic materials comes from sunlight harvested via photosynthesis, the process where light energy is used to convert water and carbon dioxide into oxygen and organic compounds. The energy not used in chemical reactions is stored as chemical bonds that can release energy when broken (McKendry, 2002). The process of harnessing energy from biomass can be compared to the generation of heat from burning coal. During combustion, biomaterial and oxygen are combined in a high temperature environment to produce carbon dioxide, water vapor, and thermal energy. The approximate chemical equation for biomass is as follows (Ciolkoszv, 2014):

$CH_{1.44}O_{0.66} + 1.03\ O_2 \rightarrow 0.72\ H_2O + CO_2 + \text{heat}$ Equation 2

The amount of generated heat depends on many factors, such as climate and biomaterial species, although it generally falls within 20 Megajoules of heat energy per kilogram of fuel substrate (Ciolkosz, 2014). Moisture in biomaterial can lower the heat content because fuels burn best when dry. For the best combustion, the water content for biomass should not exceed 20 percent (Ciolkosz, 2014). Processing biomass by grinding or drying material can make it more suitable for combustion. The types of bioenergy used for electricity production may depend on the region, such as forest byproducts in the United States, sugarcane in Brazil, or rice husks in Southeast Asia (Urban, 2011).

Biogas derives from the breakdown of biomass under anaerobic conditions. Biogas sources include agricultural waste in the natural environment, municipal solid waste, landfill, or sewage. Fermentation, another type of anaerobic digestion, can also generate biogas. Biogas contains mostly methane (55-90%) but can include carbon dioxide and hydrogen sulfide depending on its source (Ghenai, 2015). This flammable mixture may be used as a fuel, such as ethanol from sugar canes; it can also be purified to a natural gas equivalent (98% methane). Each cubic meter of methane contains approximately 50 MJ of energy, or 4-7 kWh of heat energy in one cubic meter of biogas (Alveo Water and Sanitation, n.d.). When combusted, the gas or fuel releases this energy for electrical, transportation, heating, or power generation. The following represents the chemical equation for the combustion of methane (Carnegie Mellon University, 2003).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{heat} \qquad \text{Equation 3}$$

Methane is a potent greenhouse gas. However, its extraction from waste such as landfills and its use for electricity generation reduces direct atmospheric emissions (Mohseni, 2011).

Biofuel derives from both biomass and biogas sources and includes biodiesel, methanol, butanol, and ethanol, with the latter two as the most common sources. Although fermentation via lignocellulosic material can produce bioethanol, most biofuels originate or are converted from once-living organisms through agricultural processes or anaerobic digestion (Rubin, 2008). These processes can occur naturally or in a laboratory or industrial setting. Each chemical equation for biofuel varies by the source. For example, ethanol combustion follows (Biofuel.org.uk, 2011):

$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$ Equation 4

while butanol combustion follows (Biofuel.org.uk, 2011):

$2C_4H_9OH + 5O_2 \rightarrow 8CO_2 + 10H_2O$. Equation 5

The energy content of biofuel varies by fuel source but produces around 20 Megajoules of energy per liter for ethanol and 34 Megajoules per liter for biodiesel, values that change depending on the plant species and their specific energies. Biofuel is widely used for transportation, but this paper only discusses biofuel for electricity production.

Humans have burned biomass such as wood, hay, dung, and straw for space heating, lighting, and cooking as early as 350,000 years ago. Archaeological evidence shows that the habitual use of fire began in Israel's Tabun Cave (Shimelmitz, 2014). Prior to 1840, these biological materials were the predominant energy source around the world. In developing countries today this still holds true, with almost 40 percent of the global population relying on firewood for cooking and space heating (IEA, 2006). Burning wood and raw plant material, however, can release hazardous emissions.

During the Industrial Revolution, fossil fuel energy surpassed bioenergy. Within the last two decades, however, bioenergy has been on the rise (Guo, 2014). While firewood and charcoal consumptions have remained constant, wood chips and pellets for renewable electricity generation have doubled in the last decade and some analysts predict biomass use to increase (Guo, 2014). Commercial production of cellulosic ethanol is also projected to expand, especially under U.S. government regulations (Rubin, 2008). Renewable energy research has sought to optimize biofuel production, identifying plant species with high oil yield potential, parameters and guidelines for producing desired fuel qualities, and determining oil characteristics to control quality. From 2000 to 2013, world production of biodiesel, or biofuel intended as a substitute for diesel, increased from 213 million gallons to 6.29 billion gallons, with Germany, France, Brazil, Spain, and the U.S. as some of the top producing countries (U.S. DOE, EIA, 2014). In 2015, the U.S. produced over one billion gallons of biodiesel (Atadashi, 2011). Further bioenergy research has also focused on recovering energy from waste such as municipal solid waste, food, and sewage.

One can expect to see a trend in new technologies that focus on improving combustion, energy, and production efficiencies of bioenergy. Although current fossil fuel prices do not make bioenergy production economically advantageous, the World Energy Council predicts that bioenergy consumption could increase three-fold by 2050, displacing a quarter of global natural gas consumption and possibly meeting 30 percent of the world’s energy demand, a projection that provides reason to enhance research and development of bioenergy (Guo, 2014). The next chapter will explore these technological processes.

TECHNOLOGIES THAT PRODUCE BIOENERGY

Bioenergy can be produced from many sources of biological material. This section will focus on the technology behind three types of feedstock: wood chips, biofuels, and organic waste.

The process of converting biological material into energy begins with harvesting and processing, followed by a thermochemical procedure where heat energy and chemical catalysts convert biological material into intermediate compounds. There are three common thermochemical processes: (1) combustion, which requires sufficient oxygen for oxidation; (2) gasification, which requires insufficient oxygen to prevent complete oxidation; and (3) pyrolysis, which occurs in the absence of oxygen.

THERMOCHEMICAL PROCESSES

Combustion of biomass refers to burning fuel in a boiler or stove to produce heat that can be utilized as hot air, hot water, steam or directly as electricity. Burning is the most widely used and simplest technology with a conversion efficiency into electricity at 20 to 30 percent. Wood and municipal solid waste are the most common feedstocks for combustion, although the moisture content must be low for efficiency. Combustion requires high temperatures for ignition, sufficient turbulence to mix the biological components with an oxidant, and time to complete the oxidation reaction (Equation 1). The final products of biomass are hydrogen, carbon monoxide, carbon dioxide, methane, and other hydrocarbons. CO_2 and H_2O result from complete combustion, and the burning of solid charcoal releases CO and CO_2. The release of hot gases during combustion contain about 85 percent of the fuel's potential energy; this heat can be used directly or indirectly through a heat exchanger, such as through a boiler to produce steam. Steam can be used to generate electricity, mechanical energy, or heat **(**Basu, 2010**)**.

Pyrolysis refers to the heating and decomposition of biomass in anaerobic conditions, or conditions without oxygen. It is especially useful in decomposing and fractionating biomass such as cellulosic fibers, lignin, and sugars. Its products include bio-charcoal or gases and bio-oil from the volatile fraction of biomass. The process begins with raising the temperature to release volatiles and form charcoal (Basu, 2010). Once various reactions occur, pyrolysis gas is formed. Slow pyrolysis, which occurs geologically over thousands of years with temperatures that reach 500 degrees Celsius, produces charcoal. Fast pyrolysis, or the rapid heating of material, can occur in anaerobic conditions at 450 to 600 degree Celsius, produces mainly bio-oil (60-75%) with other products including solid charcoal (15-25%) and noncondensable gases (10-20%). However, bio-oils must be further processed to lower oxygen content or filtered for particulates and alkali. Once produced, bio-oil can be used as fuel for combustion or refined into transportation fuel (U.S. DOE, Office of Energy Efficiency and Renewable Energy, 2012).

Gasification is a technique that heats biomass, converting it into combustible gas, volatiles, and ash. The technology behind gasification may vary based on the gasification agent or the reactor, but it is often more demanding because of feedstock specifications. Waste, such as municipal solid waste and agricultural residues, is a common feedstock. Gasification occurs in two endothermic steps. Biomass is first heated to over 700 degrees Celsius, which vaporizes volatiles such as hydrogen, CO, CO_2, and other hydrocarbon gases. The byproducts that remain are charcoal and ash. In the second step, the charcoal is gasified when it reacts with oxygen, steam, and hydrogen at high temperatures. The main gasification products include synthesis gas (syngas), bio-charcoal, and tar. The specific amount of each depends on the feedstock, oxidizing agent, and the process conditions (Basu, 2010). Syngas, which consists of CO, CH_4, and other hydrocarbons, can be utilized for heating or electricity generation as fuel for a Combined Heat and Power (CHP) generator, as well as production of ethanol, diesel, and chemical feedstocks (U.S. DOE, Office of EERE, n.d.**)**. Because gasification processes have a higher conversion efficiency, they are more suited for 10 MW power plants or larger to achieve full potential.

Combustion, pyrolysis, and gasification have many similarities but differ in their end uses and product ratios. When choosing a suitable mechanism for energy production, one must consider the desired final products, such as gas, bio-char, or only heat, and their end uses, such as electricity generation, heat, or transportation fuel.

The sections below describe commonly used biological materials and the technologies employed to produce bioenergy. The biological materials to be considered are woodchips, biofuel, and organic waste.

WOOD CHIPS

Woodchipping describes the process of cutting, or chipping, large pieces of wood to produce smaller, solid material of approximately 5-50 mm long. Although this procedure is often associated with mulch for gardening or landscaping, woodchips can also be used as fuel from biomass. In a process that is comparable to pulverizing conventional fossil fuels such as coal, wood chips are burned to produce steam, which powers the turbines that generate electricity. Compared to logs or planks, mechanically chipped wood has a large surface area to volume ratio. This makes the wood easier to feed steadily into a conversion system where it can be burned more uniformly and efficiently.

Wood fuel has several advantages because, as a renewable resource, it originates from a sustainable local supply. Although the combustion process (Equation 2) generates carbon dioxide, biomass in a cycle is generally considered close to carbon neutral. New biomass growth absorbs emitted carbon dioxide, and this life cycle will repeat. Recent studies have indicated that burning biomass may not actually be carbon neutral (McKendry, 2002). However, when compared to fossil fuels, wood fuel emits less carbon dioxide per heating unit during combustion. The entire process is closer to carbon neutral than combustion of oil, natural gas, or coal. Wood fuel does not contain the heavy metals or sulfur associated with coal or heavy oil, which leads to pollution and acid rain. Burning wood fuel from wood wastes prevent methane production, which lower potential greenhouse gas production (Li, 2014).

The production process begins by clearing or collecting raw materials from forest owners or forest management specialists (Figure 2). Raw materials can derive from forest wood, waste wood, pulpwood, or residues from construction, sawmills, logging, or landscaping. Ideally, these materials should be sourced as locally as possible to benefit the local economy. Once harvested, wood is delivered to a combustion site after the material is fed through a woodchipper machine. There are several types of chippers used in the industry, each with its own constraints based on the wood to be processed. These chippers are defined by well-researched factors, including operating parameters (such as angle of the chipper plate and the direction of cutting) and chip geometry (the shape and thickness of the wood chip) (Hellstrom, 2010).

Following the chipping process, the wood chips are delivered to a heating plant. These plants vary in size and may be small-scale, generating 20 to 200 kWh of heat energy, or large-scale. The type of heating plant chosen depends on the location in which electricity will be generated as well as the original raw material. For example, timber products and felled trees are more suitable for small-scale heating plants that power rural locations. In contrast, treetops and construction waste can be sent to large heating plants that power urban cities. These plants use larger feeders that can process and manage rough material and impurities (Small Giant of Bioenergy, n.d.).

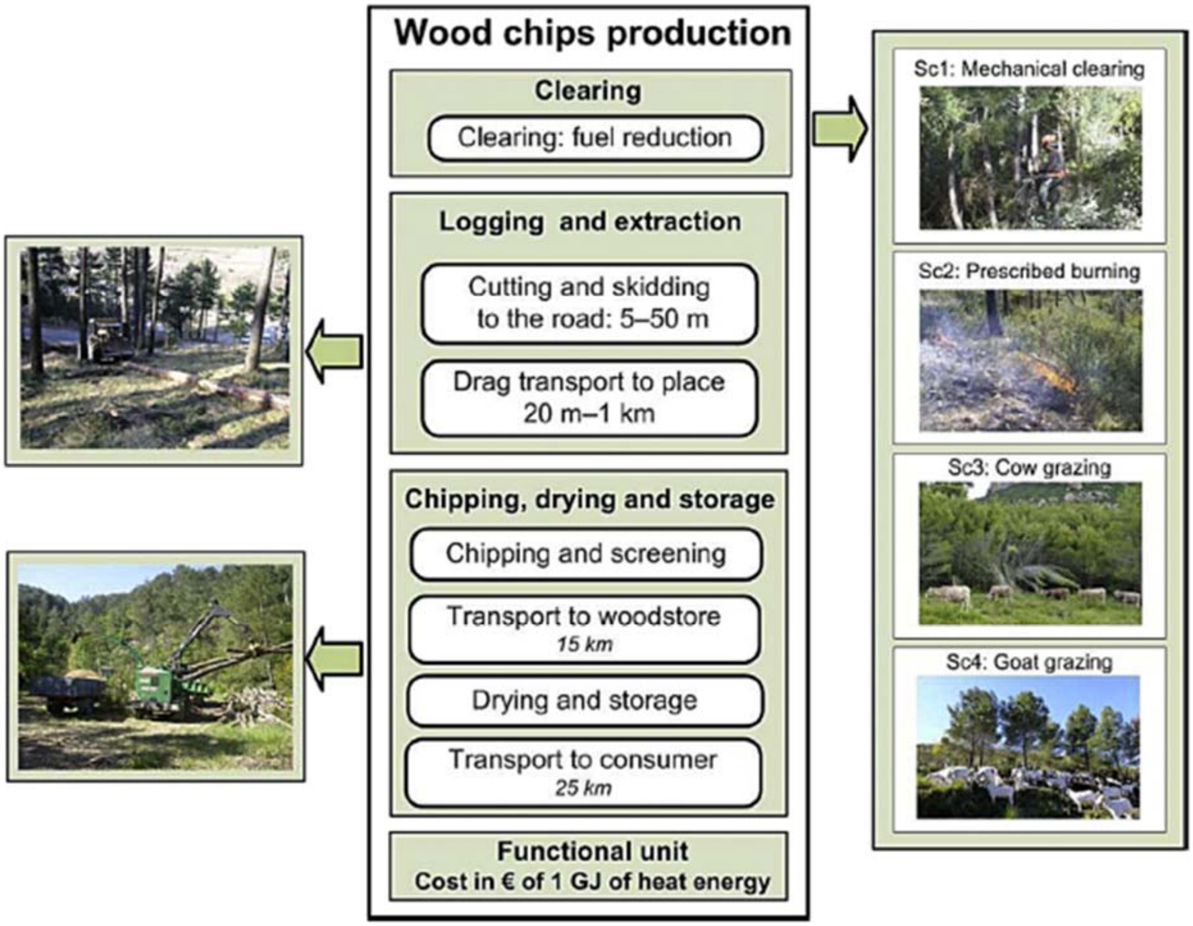
At the heating plant, the chips may be combusted, gasified, cogenerated, or cofired. Combustion (Equation 2) refers to the burning of wood chips, where the heat is transferred to a hot water boiler. Steam turbines then convert the steam to electrical power. Gasification is the heating of wood in an anaerobic environment, which releases pyrolysis gases such as carbon monoxide and hydrogen. This type of wood fuel is used for internal combustion engines, gas turbines, and microturbines. Cogeneration diverges from the traditional steam turbine method by simultaneously producing heat and electricity from wood fuel through a combined heat and power (CHP) system. Cofiring uses biomass as a supplementary energy source in coal plants, a low-cost option that reduces greenhouse gases (USDA Forest Products Laboratory, 2004).

Because of the multiple steps during production, the measurement units for wood chips change by location. Wood merchants that harvest from forest owners describe wood by volume, such as solid or loose cubic meters. To describe the energy potential of fuels, hauling operators use “tons” and heating plants use “MWh” (Central Baltic INTERREG IV A Programme & EU, 2013). A hectare of trees produces approximately 30 m^3 of felled trees, 75 m^3 of wood chips, 60 MWh of energy, or 6000 liters of fuel oil. A loose cubic meter of wood chips is approximately equal to 0.8 MWh of energy, or 80 liters of fuel oil. A solid cubic meter of felled trees equals 2.5 cubic meters of wood chips and 2 MWh of energy (Small Giant of Bioenergy, n.d.).

Several physical parameters define the efficiency of the woodchipping process. The first one is uniform quality of chips and absence of long thin pieces, or slivers. Wood chips of uniform quality allow for undisturbed function. Slivers could cause bridging or blockage when chips are fed into the system. Another parameter to consider is maximum moisture content. This also affects feed blockages but can play a role in combustion efficiency as well. Depending on the region, fresh-cut trees can have moisture contents of over 50 percent, when the advisable content should not exceed 20 percent (SEAI, n.d.c). Moist wood chips lower the quality of the fuel and the efficiency of the process by requiring a more considerable amount of energy to heat the water associated with the wood. The lower heating efficiency can cause higher energy consumption for the system, higher risk of backburn and discharge, and even problems in preserving fuel for storage (Buchmayr et al., 2015). As a result, fresh-cut material for woodchipping is often left to dry naturally; artificial drying is another option that can be costly because it requires energy expenditure. A third parameter to consider is the level of contaminant content in wood, which may increase emissions. Further parameters of interest are tree species, amount of dust and fungal spores, ash content, and even wood storage. Any of these factors can also affect the quality of the chips and the wood fuel produced (Biomass Energy Centre, n.d.).

Wood chips are traditionally used as solid fuel for electrical power or heating buildings. In some cases, coal power plants have been converted to run on wood chips; this can be a straightforward process because both can use the same type of steam turbine engines. Countries like Sweden and Finland have already increased the use of domestic wood and wood byproducts for electricity production. In Sweden, logging residues are used to generate energy for district heating companies, and the amount of this energy has increased over the years (Central Baltic INTERREG IV A Programme & EU, 2013). Finland—where 76 percent of land is forested—became the global leader in forest bioenergy in 2012, when over 24 percent of its energy consumption came from domestic wood and byproducts. This value was greater than the amount of energy produced from oil, making wood fuel the most used source of energy in Finland for the first time (Statistics Finland, 2013). Finland and Sweden’s success with wood chips for fuel shows the potential this process has in the U.S.

Figure 2. Wood Chip Production Process



Source: Reprinted from "Comparative cost evaluation of heating oil and small-scale wood chips produced from Euro-Mediterranean forests" by B. Esteban, et al., 2015, *Renewable Energy, 74*, p. 568-575.

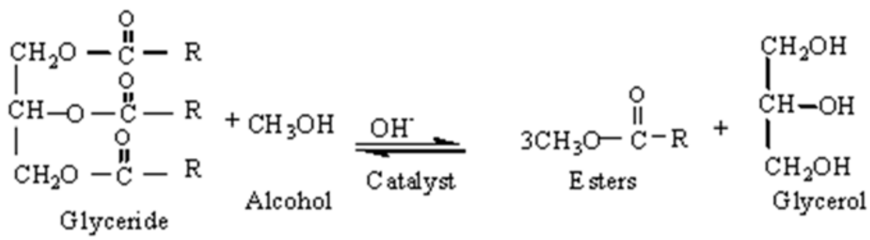
BIOFUELS

Biofuel is a liquid energy fuel that can be produced from biomass conversion or carbon fixation through photosynthesis. The feedstock comes directly from plants and microalgae or indirectly from agricultural, commercial, or industrial wastes. In contrast, fossil fuels originate through geological processes as plants and animals in the ground decompose over millions of years. The two most popular types of biofuel include bioethanol, alcohol made by fermentation, and biodiesel, oil based from long-chain alkyl esters. Bioethanol derives from crops such as wheat, woody crops, and sweet sorghum, and biodiesel derives from oil crops such as rapeseed and camelina (SEAI, n.d.b).

The most common form of biofuels today are conventional, or first-generation biofuels, made from arable crops that produce sugar, starch, and oils. Corn is the chosen material in the U.S. due to commercial-scale experience with a proven fermentation process and support from government mandates, subsidies, and tariffs. Other methods around the world use different feedstock for biofuel, such as sugarcane in Brazil and biodiesel in Argentina and Europe (U.S. DOE, National Renewable Energy Laboratory, 2015). In the U.S., gasoline is blended with bioethanol. There are multiple ways to produce biofuel, but the process generally includes chemical reactions, fermentation, and heat to break down plant sugars and starch. Products are then refined into a usable fuel.

Biofuel production cycle begins with photosynthesis. Solar energy and carbon dioxide are converted into chemical energy in biomass. Farmers then harvest the crops, which are sent to pre-treatment. There are several conversion processes but the most common are biochemical, thermochemical, and photobiological (U.S. DOE, Office of EERE, 2013).

Biochemical processes use enzyme and microorganisms as catalysts to convert biomass into desirable products. This could include breaking down carbohydrates and cellulose (hydrolysis) or fermenting and distilling sugars into ethanol (Figure 3). Many plant and animal fat oils contain triglycerides that must be separated via transesterification, a process commonly used for biodiesel (Figure 3). Transesterification reacts these triglycerides with alcohol to form esters and glycerols (Equation 6) (University of Strathclyde Engineering, n.d.).



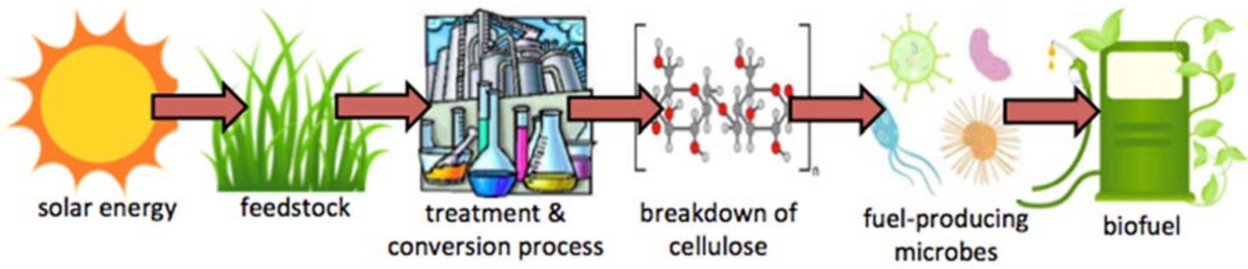
(Equation 6)

Following the breakdown of cellulose, additional microbes ferment sugars into liquid fuels (Figure 3). Remaining coproducts are converted into biobased products, such as plastics, solvents, intermediates, acids, and lubricants. Given the nature of the carbon cycle, the net carbon released during the biofuel production cycle should be close to zero (University of Illinois at Urbana-Champaign, n.d.). However, there are energy inputs throughout the conversion process, such as fossil fuels for fertilization, to power refineries, and for transportation.

Photobiological processes use natural photosynthetic activity to produce biofuels, now termed as advanced, or second-generation biofuels. Second-generation biofuels use diverse sources of biomass, which can include bacteria, algae, agricultural wastes and residues, and lignocellulosic biomass from woody crops and energy grasses such as switchgrass. Lipids converted from sugars can also become biodiesel through chemical reactions such as esterification and hydrogenation (British Petroleum, 2015). Algal biofuel production has become a popular method that both government and private companies have begun funding. The process begins with genetic engineering by selecting choice algae. Once the algae are cultivated, harvested, and separated via chemical solvents, they can be processed and refined into useable products (U.S. DOE, Office of EERE, 2014). Although second-generation biofuels have many positive features, they are not without challenges within the infrastructure and manufacturing process that complicate their integration into the energy economy and market. For example, many high-energy advanced biofuels require labs and technical processes that are costly and complex in order to generate fuel or extract cells, with commercial manufacturing facility costs ranging from $100 million to $300 million (Solecki et al., 2013).

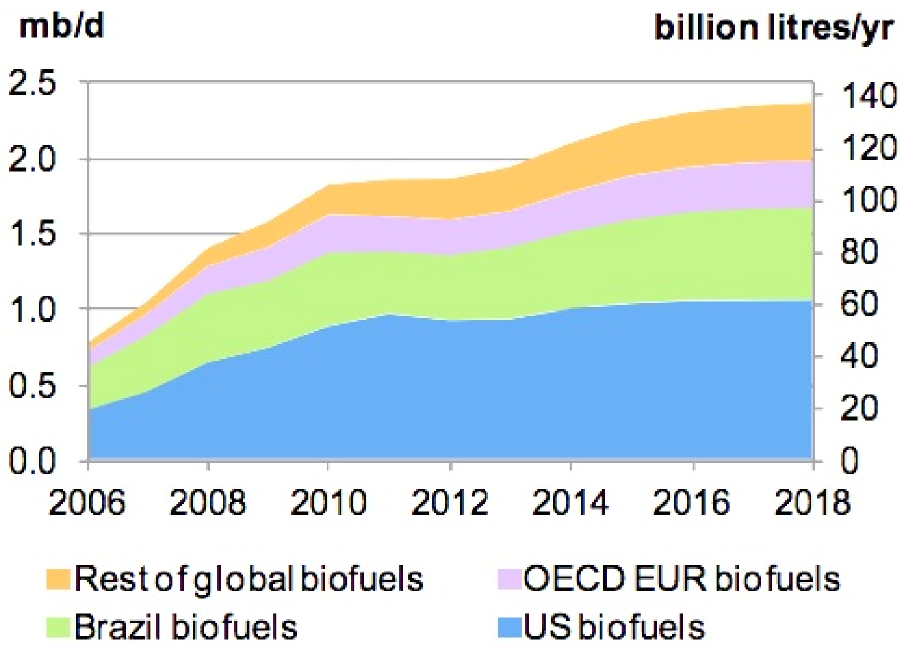
Some governments now encourage biofuel production through economic incentives, policies, mandates, subsidies, or tax credits (U.S. DOE, EIA, 2015c). For example, the U.S. Energy Independence and Security Act (EISA) of 2007 suggests a volumetric expansion to 36 billion gallons per year of renewable fuel by 2022: 15 billion from corn and 21 billion from advanced biofuels (Environmental Protection Agency, 2007). Currently, biofuels provide 3.5 percent of road transport fuels in the world (IEA, n.d.). Global biofuel supply is expected to increase; scientists project that 140 billion liters of biofuel will be produced in 2018 (Figure 4), which would provide 4 percent of global road transport fuel demand (IEA, 2013c). By 2020, biofuels may provide up to 27 percent of world transportation fuel. The uncertainties and risks of biofuel production will be discussed below.

Figure 3. Classical Approach to Biofuel Production



Source: Jennifer Den at The University of Texas at Austin, 2015, unpublished.

Figure 4. Global Supply of Biofuel From 2006-2018



Source: Reprinted from "Market Trends and Projections to 2018" by the International Energy Agency, 2013, Retrieved from https://www.iea.org/publications/freepublications/publication/2013MTRMR.pdf

ORGANIC WASTE (MUNICIPAL SOLID WASTE, SEWAGE, LIVESTOCK MANURE)

Municipal solid waste (MSW), sewage sludge (a byproduct of wastewater treatment), and livestock manure can be sources of biogas energy, and it is unlikely that they will deplete, as there will always be waste generated across any civilization. For example, Americans generated 254 millions ton of garbage, or MSW, and recycled about 87 millions tons in 2013 (Figure 5) (U.S. DOE, EPA, 2016).

Waste-to-energy has become more attractive due to its relatively low air and water pollution rates, useful byproducts, feasibility in both large and small-scale industries, and the production process's allowance of high water content, which is not the case for many conversion technologies such as combustion (IEA, 2013a). The energy conversion process for organic waste uses anaerobic digestion, a biochemical conversion technique. Anaerobic digestion is a naturally occurring microbial method that occurs when organic material decomposes in the absence of oxygen to release biogas. This process converts unstable pathogens and nutrient rich substrates into more stable material. Dried leftover substrate can be used as fertilizer or composted and reused as bedding material. The biogas produced in this process is composed of approximately 65 percent methane, 35 percent carbon dioxide, and the rest as trace gases (Ileleji et al., 2008).

There are four stages to produce biogas from anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Figure 6). Hydrolysis is the process where specific bacteria split long chain organic compounds into simple compounds, such as proteins into amino acids or carbohydrates into sugars. The products of hydrolysis are then sent to the acidogenesis phase, where acid-forming bacteria break these products into short chain fatty acids. This process is used in digesting manure. Some of the products from acidogensis include acetic acid, hydrogen, and carbon dioxide, which act as initial products for methane formation. The third phase is acetogenesis, or the use of acetic-forming bacteria to break down organic acids and alcohols into more acetic acid, hydrogen, and carbon dioxide. The last phase, methanogenesis, also used in manure digestion, converts the acetogenesis products into biogas via mioorogranisms (SEAI, n.d.a). Anaerobic digestion of biomass varies by temperature, which can influence speed and stability of the process. There are two temperature ranges: mesophilic (32-45 degrees Celsius) or thermophilic (50 to 65 degrees Celsius). As optimum growth for methane bacteria occurs at the mesophilic range, many biogas facilities operate at this temperature for high gas yields and process stability. Thermophilic digestion is most advantageous when using animal byproducts or agricultural wastes. Although this temperature produces higher gas yields, the process is more sensitive to disturbances.

Tables 1-4 list some of the many sources of waste material: MSW, agricultural waste, manure, and energy crops and their associated methane yields (Appels et al, 2011). Most sources follow the general process mentioned above, but MSW and manure will be further described, as there are additional techniques involved.

Municipal Solid Waste

Source separation is an important first step that removes compounds such as heavy metals not suitable for anaerobic digestion to produce a higher quality end product. However, the composition of MSW’s organic fraction may vary based on location, season, and the type or quality of waste. For example, rural areas produce higher biodegradable waste, whereas urban areas would have a higher percentage of plastic (Appels et al., 2011).

Anaerobic digestion technology for MSW can be classified according to the content of total solids to be digested in wet or dry digestion. Low solid contents (less than 12 percent) undergo wet digestion, while high solid contents (22-40 percent) undergo dry digestion (IEA, 2013a). Wet digestion, established in Europe during the 1980s, begins with homogenizing material in a mixing unit. A spiral press then separates the material into a liquid and solid phase. The liquid matter goes into digestion, whereas the solid fraction is processed for composting. The main limitation to this technique is the large amount of water used, which results in expensive post-treatment technology and high reactor volume. Wet digesters can operate as co-digestion plants; other liquid or solid material such as sewage sludge can be digested at the same time as MSW (IEA, 2013b).

There are three common dry digestion processes, also developed in the 1980s: Dranco, Kompogas, and Valorga (IEA, 2013a). The Dranco reactor passes feedstock vertically through a reactor and the digestate is recycled. The Kompogas process uses a horizontal flow, where the digester is mixed with a paddle stirrer. The Valorga digester is vertical but the feedstock enters from the bottom (Figure 7).

Following digestion, the MSW can then be treated and converted to energy. The three types of thermochemical procedures can be applied for treatment of waste: combustion, gasification, and pyrolysis. While combustion furnaces are the most commonly used technology, pyrolysis plants exist in both Japan and Germany, demonstrating their potential application in the U.S. For example, approximately 30,000 tons of MSW are treated annually in a pyrolysis plant in Burgau, Germany (IEA, 2013b).

Landfill gas (LFG) contains 50-60 percent methane and 40-50 percent carbon dioxide and is another alternative source of MSW energy that allows facilities to be built nearby or onsite. Landfills are the most widespread method of solid waste disposal in the world, responsible for approximately 8 percent of methane emissions. Waste may take years to decompose and soluble constituents may leach into and pollute soil and groundwater. A common option is waste incineration, but like all combustion processes, it can release harmful gases to the atmosphere, such as nitrogen oxides and carbon dioxide (Tsai, 2007).

Landfill gas (LFG) is created when organic waste in a MSW landfill decomposes. Instead of escaping into air, LFG can be captured and converted into energy (Environmental Protection Agency, n.d.). Collection is accomplished through trenches or wells that are installed into the waste. The gas is then piped to be treated or flared. Flaring removes gas that does not warrant direct use or electricity generation and can also control excess gas extraction spikes. During treatment, impurities, condensates, and particulates are removed from LFG. Treatment systems may be divided into multiple processing systems if the gas will be used for electricity generation: primarily to remove moisture and secondarily to clean up constituents such as sulfur compounds. For electricity generation, gas turbines or internal combustion engines are employed. If the gas is used directly, which usually means within five miles of the landfill, boilers, dryers, or process heaters are used. This process is most similar to that of using natural gas. Although LFG is much cheaper than natural gas, it also holds only half of its heating value (Tsai, 2007).

Sewage Sludge

Wastewater treatment facilities generate sewage sludge as a byproduct during treatment. By using anaerobic digestion, facilities can treat sludge and reduce almost 40 percent of the overall load of biosolids to be disposed. Anaerobic digestion, now widely considered as both economical and environmentally friendly, stabilizes sludge and reduces pathogenic microorganisms. The anaerobic digestion of sewage sludge is said to yield the highest biogas production capacity worldwide, generating large amounts of methane. However, the methane yield of the sludge depends on its composition (Appels et al., 2011).

There are two phases of wastewater sludge treatment. In the first step, all incoming flows of sludge are combined and the mixture is heated to accelerate biological conversion for 10-20 days. The mixture undergoes further digestion without mixing to promote separation. This process generates its own heat as the digested sludge begins to settle. Following treatment, the sludge is dewatered, thickened, and stabilized to reduce pathogen levels and odors. The entire anaerobic digestion procedure, especially secondary-treatment of sludge, generates biogas by breaking down organic matter into carbon dioxide and methane for energy use (Nazaroff & Alvarez-Cohen, n.d.).

For example, the Albert Lea facility in Minnesota processes 12 million gallons of sewage per day, with 4.5 million gallons treated into sludge. It produces 75,000 cubic feet of biogas and the four microturbines at the facility each generates 30 kW. At peak production, this facility can produce 2,500 kWh/day of energy and 28,000 Btu/day of heat. For a renewable resource, this is a significant portion of energy when one considers that an average residential customer uses approximately 30 kWh/day (Nazaroff & Alvarez-Cohen, n.d.).

Manure

Key states in the U.S. with large amounts of agricultural residues and manure include Iowa with 31 million tons, Arkansas with 10.3 million tons, Texas with 9.8 million tons, and California with 9.2 million tons. Figure 8 shows the projected agricultural residues and manure availability by county in 2030. The most abundant agricultural residues and manure resources (500,000 to 1.2 million dry tons) are located in the upper Midwest and central California. Several other agricultural regions across America also have potential to produce bioenergy.

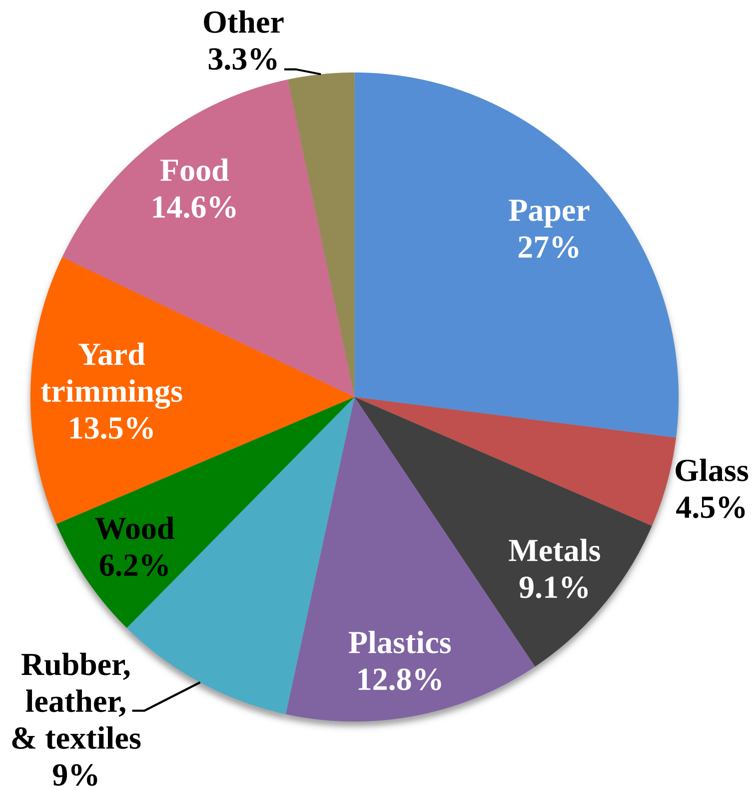
The methane potential of manure includes both the animal feces and the bedding material. Due to its high nitrogen content, manure is suitable for the development of anaerobic microorganisms. Manure is frequently co-digested with other wastes with low nitrogen concentration to reduce ammonia content, which may inhibit the digestion process. Natural degradation of manure leads to uncontrolled methane emission, which has an undesirable effect on the climate. By controlling this degradation via anaerobic digestion in a facility, facilities can reduce methane discharge (Appels et al., 2011).

The general process of anaerobic digestion of manure begins with liquefaction of the organic substrate by bacteria. This is followed by acidogenesis, or acid production via acid-forming bacteria, and methanogenesis, or methane production via methane-producing bacteria (Figure 9). The effluent can often be further separated into solid and liquid fractions. For example, solid fraction from cow manure may be recycled as bedding. Its improved nutrient availability, reduced acidity, and reduced odor also allow digested manure to be used as fertilizer (Illeleji et al., 2008).

Poorly managed waste can produce residuals that can affect human health, environment, and the economy. It often results in downstream costs higher than what it would have cost to manage the waste appropriately from the beginning. Waste can contribute to greenhouse gas emissions from methane release during biodegradation (IEA, 2013b). However, properly managed waste coupled with clean energy or electricity generation is a way to reduce waste and greenhouse gases with one process. Even in developing countries, biogas projects can help small farmers and villages by producing electricity with reduced fuel crops. For example, biogas has long been used in small pig farms in Asian countries and Latin America (IEA, 2013b). Not only does this enhance the incomes of pig farmers, but it also captures methane for on-farm use and treats effluent so there is safe water for irrigation and drinking. The methane can be captured and ignited for cooking and heating. In more developed countries, small-scale or medium-sized operations can also find additional revenue by selling bioenergy to clients or reducing their own on-site energy costs.

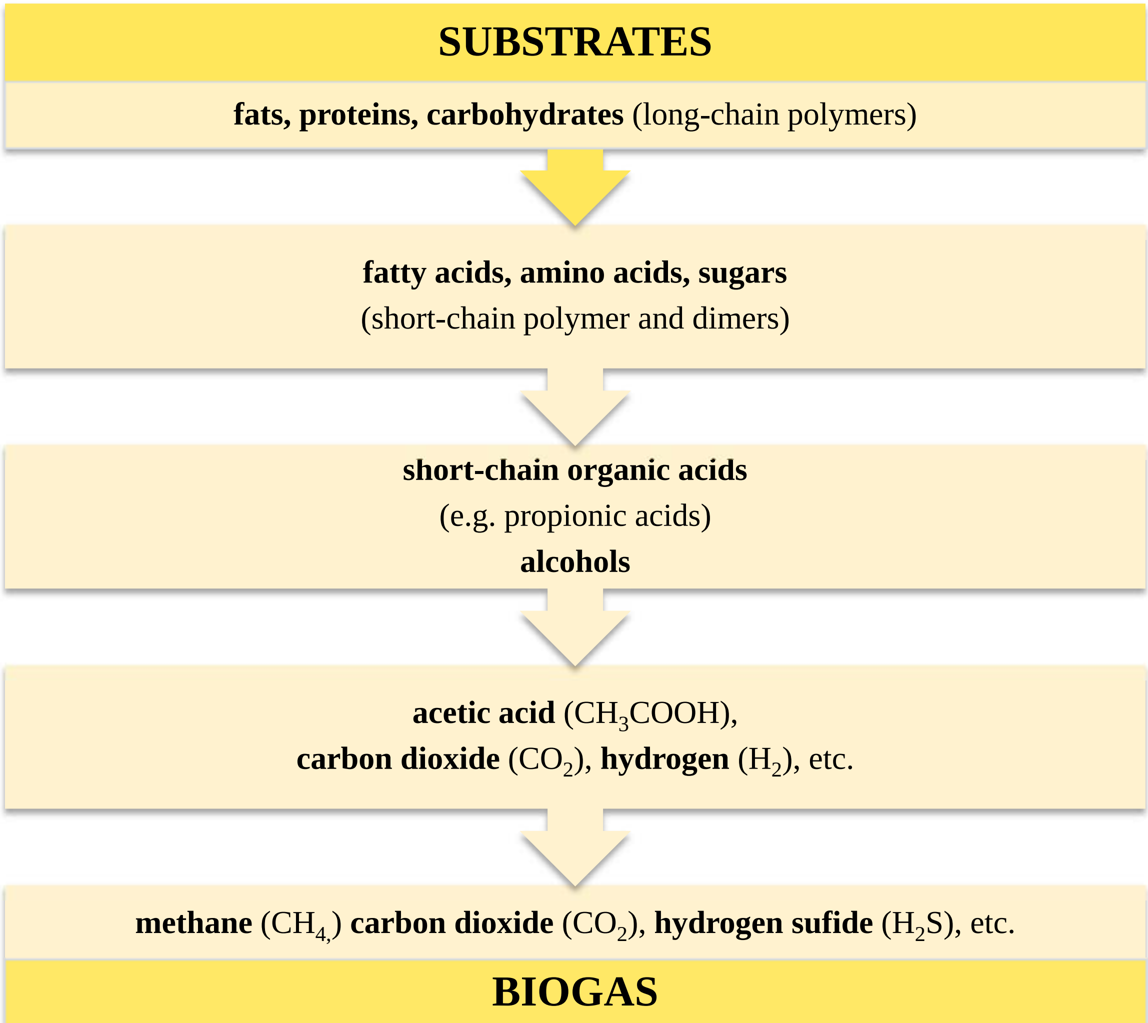
This section shows that through different technologies, bioenergy can be generated from many sources of biological material. These technologies employ thermochemical processes such as combustion, pyrolysis, and gasification, which are techniques that can also vary product ratios and determine a feedstock's end use. Wood chips are harvested, processed and chipped, and heated for energy. Biofuel crops are harvested and treated with enzymes and microorganisms to undergo chemical reactions and biochemical processes. Once cellulosic breakdown has occurred, plant sugars are fermented into liquid fuel. Organic waste comes in many different forms but is processed in one of two ways, using heat (incinerating material) or anaerobic digestion (producing biogas from anaerobic enzymes). The following section will reference three cost-benefit studies that analyze these technologies.

Figure 5. Total Municipal Solid Waste Generation in 2013 By Material



Source: Reprinted from "Municipal Solid Waste" by the U.S. DOE Environmental Protection Agency, 2014, Retrieved from https://www3.epa.gov/epawaste/nonhaz/municipal/

Figure 6. Anaerobic Digestion Process



Source: Reprinted from "Four phases to produce biomass" by the Sustainable Energy Authority of Ireland, n.d., Retrieved from http://www.seai.ie/Renewables/Bioenergy/Bioenergy_Technologies/Anaerobic_Digestion/The_Process_and_Techniques_of_Anaerobic_Digestion/

Table 1. Methane Yield for MSW

Type of MSW	Methane Yield (m^3/kg Organic Dry Substance)
Mechanically sorted (fresh)	0.22
Mechanically sorted (dried)	0.22
Hand sorted	0.21
Grass	0.21
Leaves	0.12
Branches	0.13
Mixed Yard Waste	0.14
Office Paper	0.37
Corrugated Paper	0.28
Printed Newspaper	0.10

Table 2. Methane Yield for Fruit & Vegetable Waste

Types of Fruit & Vegetable Waste	Methane Yield (m^3/kg Organic Dry Substance)
Mango peels	0.37-0.52
Banana peels	0.24-0.32
Orange peels	0.46
Orange pressings	0.50
Mandarin peels	0.49
Mandarin pressings	0.43
Whole mandarins (rotten)	0.50
Lemon pressings	0.47
Grape pressings	0.28
Pomegranate peels	0.31
Tomatoes (rotten)	0.21-0.38
Onion exterior peels	0.40
Garden beet leaves	0.23
Carrot leaves	0.24
Cabbage leaves	0.31

Table 3. Methane Yield for Manure

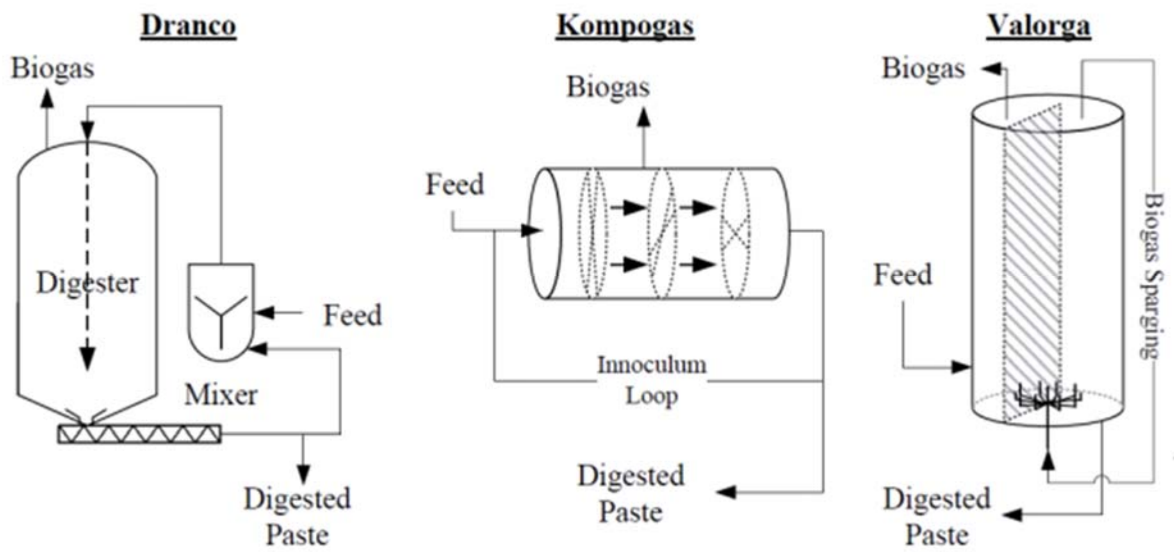
Type of Manure	Methane Yield (m^3/kg Organic Dry Substance)
Pig	0.36
Sow	0.38
Dairy cattle	0.15

Table 4. Methane Yield for Energy Crops

Crop	Crop Yield (ton /hectare)	Methane Yield (m^3/kg Organic Dry Substance)
Sugar beet	40-70	0.39-0.41
Fodder beet	80-120	0.40-0.42
Maize	40-60	0.29-0.34
Corn cob mix	10-15	0.35-0.36
Wheat	30-50	0.35-0.38
Triticale	28-33	0.32-0.34
Sorghum	40-80	0.29-0.32
Grass	22-31	0.29-0.32
Red clover	17-25	0.30-0.35
Sunflower	31-42	0.23-0.30
Wheat grain	6-10	0.37-0.40
Rye grain	4-7	0.30-0.41

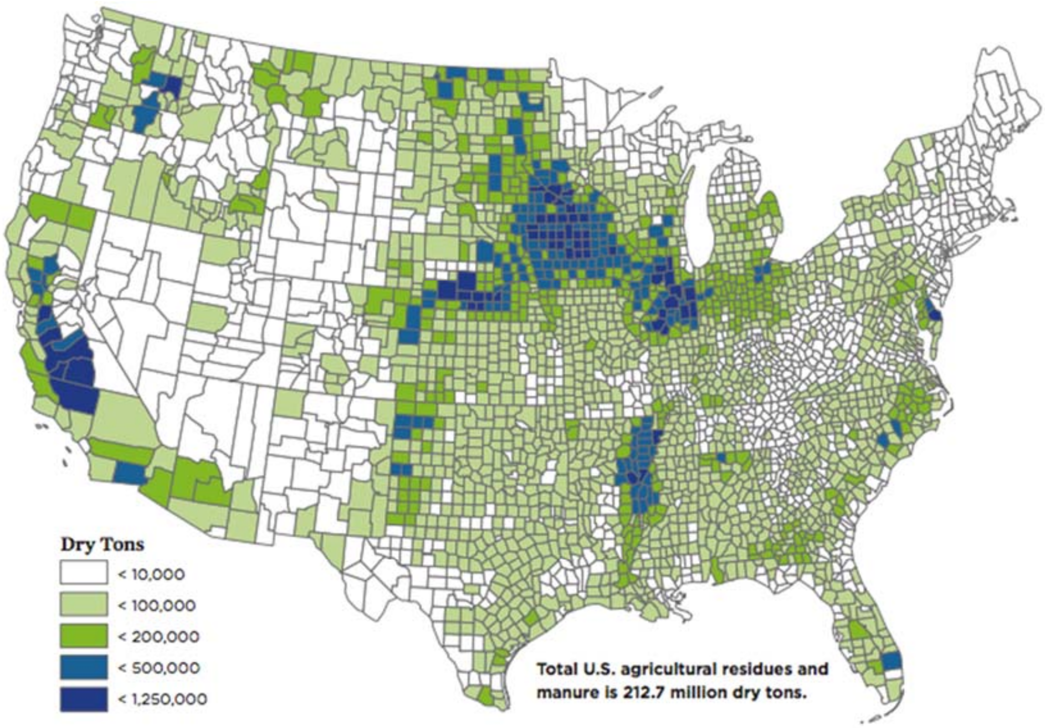
Source: Reprinted from “Anaerobic digestion in global bio-energy production: Potential and research challenges” by L. Appels, et al., 2011, *Renewable and Sustainable Energy Reviews, 15*, p. 4295-4301.

Figure 7. Dry (Solid Waste) Digestion Processes



Source: Reprinted from "Waste to Energy" by the International Energy Agency, 2013, Retrieved from http://www.ieabioenergy.com/wp-content/uploads/2014/03/ExCo71-Waste-to-Energy-Summary-and-Conclusions-28.03.14.html

Figure 8. Agricultural Residues and Manure Availability by County in 2030



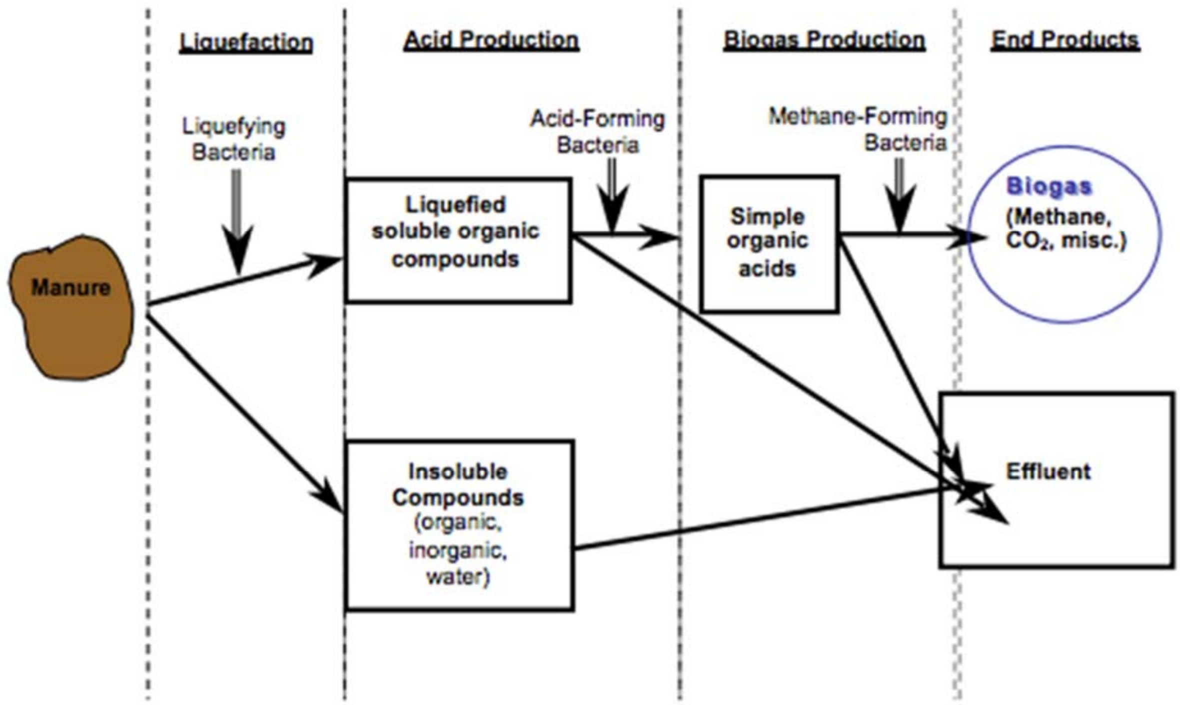
While the most abundant agricultural residues and manure resources are located in the upper Midwest and central California, agricultural areas around the country can contribute to low-carbon bioenergy production.

Note: Agricultural residues include corn and small grains, cotton, orchard prunings, and other parts of the plant not needed for food or other uses.

SOURCE: ADAPTED FROM UCS 2012.

Source: Reprinted from “Turning Agricultural Residues and Manure into Bioenergy” by the Union of Concerned Scientists, 2014, Retrieved from http://www.ucsusa.org/sites/default/files/legacy/assets/documents/clean_vehicles/Agricultural-Residue-Ranking.html

Figure 9. Anaerobic Digestion of Manure



Source: Reprinted from "Basics of energy production through anaerobic digestion of livestock manure" by K. Illelji, et al., 2008, Retrieved from https://www.extension.purdue.edu/extmedia/ID/ID-406-W.html